PLANETARY PROBE LASER PROPULSION CONCEPT
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ABSTRACT

The objective of this paper is to study a moon-based laser propulsion system to reduce spacecraft fuel consumption and travel time. The study considers a small satellite demonstration in lunar orbit and the proposed system would ultimately be expanded for missions across the solar system. A design tool was written in Microsoft Excel to simulate a laser-assisted interplanetary probe system, either using laser-sail or ion engine propulsion. This design tool calculated that a 1000 W laser with a 75 cm diameter mirror would result in a change of velocity of 1.92×10^{-1} m/s after 100 days of operation for a probe using laser-assisted solar sails. Using the same laser, a laser-assisted ion engine would result in a change of velocity of 529 m/s after 100 days of operation. The change in velocity when using a laser-assisted ion engine is enough to significantly reduce travel time. This particular application can help expand interplanetary travel by providing infrastructure to reduce travel time while decreasing the mass of the spacecraft.

1. INTRODUCTION

The scope of interplanetary travel has been limited by the amount of fuel that a probe can be designed to hold. With the concept of laser propulsion, probes can be designed to go deeper into the solar system, while maintaining reasonable payload requirements. On higher end laser propulsion systems, travel time can also be significantly reduced. This paper is studying two concepts for a laser propulsion system demonstration, using either laser sail propulsion or a laser beam to power an ion engine.

2. BACKGROUND

Lunar probes have recently been sent to the moon, looking for materials needed for further expansion into the solar system. One recent such mission was the Lunar Prospector, shown in Fig. 1.

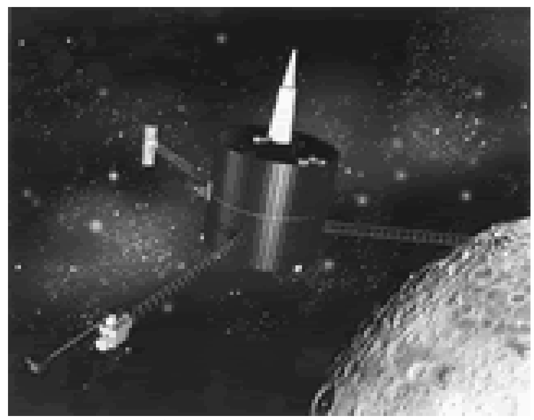

Fig. 1. Lunar Prospector

The mission characteristics of the Lunar Prospector are shown in Tab. 1.

Tab. 1. Lunar Prospector Mission Characteristics

	Lunar Prospector
Travel time (hr)	105
Launch mass (kg)	296
Spacecraft dry mass (kg)	158
Fuel mass (kg)	138
Launch vehicle	Athena II
Mission Cost (Millions)	$62.80

The mission trajectory for the Lunar Prospector is shown in Fig. 2.

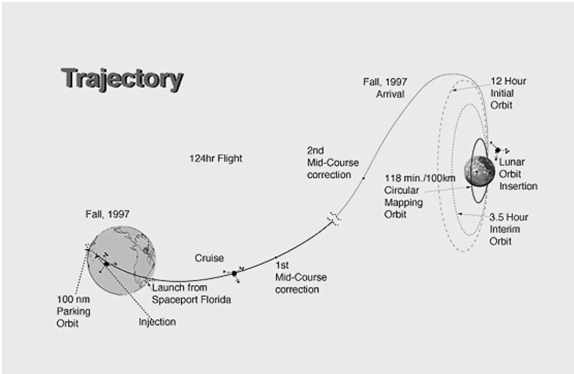

Fig. 2. Lunar Prospector Mission Trajectory

The Lunar Prospector was chosen as a benchmark because it was a recent mission of the size typical for interplanetary probes.

2.1 Mission Objective

The mission objective for this paper is to study two concepts for a possible laser propulsion demonstration in low Earth orbit to reduce spacecraft fuel and travel time. With a successful demonstration, a more permanent system could be built in lunar orbit or at one of the LaGrange points around Earth to assist probes travelling throughout the solar system. The demonstration would involve beaming the laser to a small probe over short distances in order to measure the boost provided by the additional power.

3. THEORY

To understand the Planetary Probe Laser Propulsion Concept (PPLPC), some basic knowledge of laser fundamentals is needed. The size of the power system can be estimated using Eq. 1

$$P_{laser} = \frac{1400}{R_{sl,au}^2}\varepsilon_{las}\pi R_{array}^2 (W) \qquad (1)$$

This equation, R_{array} is the radius of a disc-shaped solar array, in metres. The efficiency of the power system converting sunlight to laser power is ε_{las} and the separation between the Sun and laser power station is $R_{sl,au}$, in Astronomical Units. The 1,400 W m^2 is the solar irradiance on an object 1AU from the Sun.

The size of the laser optics can calculated with the relationship in Eq. 2

$$\frac{2.44\lambda_{laser}}{D_{las-tran}} = \frac{2R_{sail}}{D_{las-ship,\max}} \qquad (2)$$

The laser wavelength is given by λ_{laser} and the diameter of the laser transmitting optics, $D_{las-tran}$, both in metres. The maximum separation between laser power station and the probe is $D_{las-ship,max}$, in metres. The radius of the solar sail is given by R_{sail}, in metres.

The acceleration of the probe using a laser sail is a function of the power received from the laser system can be shown in Eq. 3

$$ACC_{laser-sail} = \frac{(1+REF_{sail})}{M_s c}P_{laser}\left(\frac{m}{s^2}\right) \qquad (3)$$

This equation is for the case of a fully opaque spacecraft sail. The reflectivity of the solar sail is REF_{sail} and the spacecraft mass is M_s, in kilogrammes. The speed of light is c, in metres per second. If solar sail is not fully opaque replace $(1+REF_{sail})$ in Eq. 2 with $(ABS_{sail} + 2REF_{sail})$ where ABS_{sail} is the sail fractional absorption.

The acceleration of the probe using an ion engine is a function of the power received from the laser system can be shown in Eq. 4

$$ACC_{ion-engine} = \frac{2\eta_t P_{laser}}{M_S g Isp} \qquad (4)$$

As with Eq. 3, M_s is the spacecraft mass, in kilogrammes, g is the acceleration of gravity, and η_t is the total efficiency of the ion engine.

4. METHODOLOGY

A simple design tool was created in Microsoft excel to study the two laser propulsion systems. The program was sectioned into four parts, Power Beam Sizing, Laser Sail Acceleration, Ion Engine Acceleration, and Power Beam Optics. This design tool can be seen in Fig. 3.

Fig. 3. Excel Design Tool

The Power Beam Sizing portion of the design tool calculates the size of the array necessary to beam a set amount of power to propel a planetary probe. This set amount of power can be input into the design tool and will depend on the design parameters.

The Laser Sail Acceleration portion of the design tool calculates the acceleration that the power beam could provide to a probe utilizing laser sail propulsion. The Ion Engine Acceleration portion of the design tool calculates the acceleration that an ion engine could provide if powered by the laser beam. The defaults for the total efficiency of the ion engine and specific impulse were based on the HiPEP engine. These can be changed with inputs to the design tool.

The Power Beam Optics portion of the design tool calculates the diameter of the receiver necessary for the probe to receive power from a laser using given optical specifications. It will also calculate the optics necessary to beam power to a given receiver.

5. RESULTS AND DISCUSSION

With the design tool we created, we examined the acceleration created by potential laser propulsion systems. These results are displayed in Fig.4 and Fig.5.

Beam Power (W)	Vehicle Size (kg)	Acceleration (m/s^2)	deltaV after 100 days (m/sec)
1000	300	2.22376E-08	0.192132919
1000	200	3.33564E-08	0.288199378
1000	100	6.67128E-08	0.576398757
1000	50	1.33426E-07	1.152797513
1000	25	2.66851E-07	2.305595026
10000	300	2.22376E-07	1.921329188
10000	200	3.33564E-07	2.881993783
10000	100	6.67128E-07	5.763987565
10000	50	1.33426E-06	11.52797513
10000	25	2.66851E-06	23.05595026
100000	300	2.22376E-06	19.21329188
100000	200	3.33564E-06	28.81993783
100000	100	6.67128E-06	57.63987565
100000	50	1.33426E-05	115.2797513
100000	25	2.66851E-05	230.5595026
1000000	300	2.22376E-05	192.1329188
1000000	200	3.33564E-05	288.1993783
1000000	100	6.67128E-05	576.3987565
1000000	50	0.000133426	1152.797513
1000000	25	0.000266851	2305.595026
10000000	300	0.000222376	1921.329188
10000000	200	0.000333564	2881.993783
10000000	100	0.000667128	5763.987565
10000000	50	0.001334256	11527.97513
10000000	25	0.002668513	23055.95026

Fig. 4. Acceleration generated with laser sail propulsion system and DeltaV after 100 days of Operation.

Beam Power (W)	Vehicle Size (kg)	Acceleration (m/s^2)	deltaV after 100 days (m/sec)
1000	300	6.13333E-05	529.92
1000	200	0.000092	794.88
1000	100	0.000184	1589.76
1000	50	0.000368	3179.52
1000	25	0.000736	6359.04
10000	300	0.000613333	5299.2
10000	200	0.00092	7948.8
10000	100	0.00184	15897.6
10000	50	0.00368	31795.2
10000	25	0.00736	63590.4
100000	300	0.006133333	52992
100000	200	0.0092	79488
100000	100	0.0184	158976
100000	50	0.0368	317952
100000	25	0.0736	635904
1000000	300	0.061333333	529920
1000000	200	0.092	794880
1000000	100	0.184	1589760
1000000	50	0.368	3179520
1000000	25	0.736	6359040
10000000	300	0.613333333	5299200
10000000	200	0.92	7948800
10000000	100	1.84	15897600
10000000	50	3.68	31795200
10000000	25	7.36	63590400

Fig 5. Acceleration generated with ion engine propulsion system and DeltaV after 100 days of Operation.

Fig. 4 and Fig.5 show that using the laser to power the ion engine would be much more effective. The demonstration, using the 1000 W laser, would provide an acceleration boost of $6.13*10^{-5}$ m/s^2, to a 300 kg probe using ion engine propulsion, but would only provide an acceleration boost of $2.22*10^{-8}$ m/s^2 for a 300 kg probe using laser sail propulsion. After 100 days of operation, the laser demonstration could provide a change in velocity of 529 m/s to the 300 kg probe using ion engine propulsion. After 100 days of operation, the laser demonstration could provide a change in velocity of 0.192 m/s. The ion engine would be the preferable laser propulsion design option in all but the most extreme cases.

6. CONCLUSIONS

After studying the two laser propulsion design systems, the laser powered ion engine appears to be the more useful of the two options. If this system is expanded and implemented, it can help significantly reduce travel time and increase the range for interplanetary probe missions.

7. REFERENCES

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